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A METEOROID ENVIRONMENT FOR NEAR-EARTH, CISLUNAR, AND NEAR-LUNAR OPERATIONS

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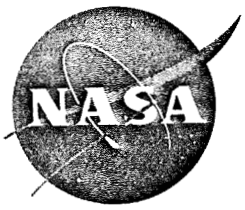

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
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Prepared by: P. B. Burbank
Meteoroid Technology and Optics Branch

B. G. Cour-Palais
Meteoroid Technology and Optics Branch

W. E. McAllum
Meteoroid Technology and Optics Branch

Authorized for Distribution:

Warren Gillespie, Jr.
for Maxime A. Faget
Assistant Director for Engineering and Development

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A METEOROID ENVIRONMENT FOR NEAR-EARTH, CISLUNAR, AND NEAR-LUNAR OPERATIONS

SUMMARY

A model meteoroid environment is presented for near-earth, cislunar, and lunar operations. This environment is the result of several trial model environments that have been assessed and modified by spacecraft manufacturers, scientists, and engineers associated with space environment and hardware of spacecraft. The environment includes the physical and dynamic characteristics of sporadic and stream meteoroids and where applicable, the secondary flux for the lunar surface.

INTRODUCTION

One of the principle parameters to be considered in the design of space vehicles is the hazard imposed by extraterrestrial debris. The impingement of high velocity particles with thin-skinned pressurized structures can result in a minute puncture and gradual depressurization of the space vehicle or catastrophic rupture by explosive decompression. Interaction of the vaporized skin, caused by absorption of the kinetic energy of the impinging particle, with the space vehicle atmosphere can result in oxidative explosions with resultant high temperature and pressure fluctuations. Impingement of high velocity particles can also result in failure of various spacecraft components or failure of heat shield during reentry due to puncture. The hazard includes damage by erosion to extremely thin surfaces, solar panels, viewing ports and optical systems.

The purpose of this paper is to furnish a design criteria for the meteoroid environment of the earth-moon system and is not meant to be a treatise on meteoroid technology nor a compilation of papers related to meteoroid criteria. This meteoroid environment is the development of several trial model environments that have been assessed and modified by spacecraft manufacturers, scientists, and engineers associated with space environment and hardware of spacecraft.

The scope will include the physical and dynamic characteristics of individual particles in space and the flux of both sporadic and stream meteoroids. The environment will be applicable to interplanetary space near earth (at an altitude of $\geq$ 70 km), cislunar and lunar (to the surface of the moon). The density and orbit (velocity) will be defined

for a range of meteoroid sizes from a minimum defined by Poynting-Robertson effect to a maximum of one gram.

The continued work in the many aspects of space environment will require a continued updating of this criteria to include the most recent and accurate data.

SYMBOLS

a	Semi-major axis (astronomical units)
AU	Astronomical unit
F	Ratio of accumulative meteor stream flux to the sporadic meteor flux
H	Altitude from shielding body
m	Mass, grams
N	Flux (particles/unit area - unit time) units of area and time are defined with each equation
p	Point of perihelion
q	Perihelion distance (astronomical units)
R	Radius of shielding body
S	Sun
V	Velocity, km/sec
VM	Visual magnitude
V_s	Velocity of shower, km/sec
γ	Heliocentric position of the vernal equinox, deg
ϵ	Eccentricity
ζ	Shielding factor
θ	$\frac{1}{2}$ the angle subtended by the shielding body

i	Inclination of meteoroid orbital plane
π	$\Omega + \omega$ longitude or perihelion, deg
ρ	Density, gms/cm^3
Ω	Longitude of ascending node, deg
$\overline{\Omega}$	Ascending node
$\underline{\upsilon}$	Descending node
ω	Latitude of perihelion

Subscripts:

$0,n$	Meteor visual magnitude

TERMINOLOGY

In this paper the word "meteoroid" is used as a general term referring to particles traveling in space. A "meteor" is the visual, photographic, or electromagnetic phenomena associated with the interaction of a meteoroid with the earth's atmosphere. A "meteorite" is that portion of a meteoroid that has survived the interaction with the earth's atmosphere and is found on the surface of the earth. Micrometeorite is a qualitative term for meteorites that have a large surface area to mass ratio and the energy of interaction with the earth's atmosphere is radiated without large physical changes. "Sporadic" meteoroids are individual particles having random orientation and no known relation with any other particle. "Stream" meteors consist of particles in relatively close proximity, each particle having a similar, but independent orbit about the sun.

GENERAL REMARKS ON SPACE DEBRIS

The presence of space debris within the solar system is indicated by the following phenomena:

1. The solar corona and zodiacal light are caused by the reflection and refraction of sunlight by particles ranging in size from about 0.2 micron to 300 microns in diameter that are located between the earth and the sun. A similar phenomena denoted as

gegenschein emanates from particles at distances greater than 1 A.U.

2. Ground-based observations of meteors.

3. The recovery of meteorites from many different areas on the earth's surface and micrometeorites from the polar regions.

4. The initial results obtained with particle-flux sensors on rocket probes and earth satellites at altitudes greater than 100 km.

In size, the debris ranges from the body that caused the largest meteorite crater found on the earth, the two mile diameter Ungava crater in Quebec, to the particle limited by solar pressure and the Poynting-Robertson effect. The Poynting-Robertson effect as defined in reference 1, is the drag caused by the reemission and reflection of incident solar radiation. Radiation emitted by the particle in the direction of motion has a slightly higher frequency, and therefore higher energy, than the radiation emitted in the opposite direction. The resultant radiation pressure differential decelerates the particle. As an example, the Poynting-Robertson effect would cause a 500 micron diameter particle located in Halley's comet and having a density of 4 gm/cm^3 to spiral into the sun in 10^7 years. Solar radiation pressure imposes a lower limit on the Poynting-Robertson effect and all particles smaller than the limit are swept out of the solar system. The limiting diameter is presented (ref. 2) as 0.3 microns for a metallic particle and 0.2 microns for a dielectric particle. In reference 3, the smallest particle diameters required to produce the zodiacal light is given as 0.16 micron to 4.1 microns for the metallic and the dielectric particles, respectively. The existence of particles smaller than the radiation pressure limit is explained by a continuous creation by the disintegration of the larger "fluffy" particles found by Soberman, (ref. 4).

There are at least five hypothesized sources of space debris: (1) cometary ejection or disintegration - probably contributes more than 90 percent of the total space debris (2) grinding and fragmentation of asteroids - contributes between 2 and 10 percent of the total (3) ejected material from the surface of the moon (4) interstellar capture - this probably contributes about 1 percent of the total (5) condensation of interplanetary gas.

Meteoroid Composition

The source of space debris gives an indication of the meteroid density. Asteroids are believed to vary from 3 to 9 gm/cm^3. The

composition of asteroidal meteoroids is inferred from analysis of meteorites. The meteorites have been categorized in the following table from reference 5.

Classified Meteorite Falls
(Prior's Catalogue 1953)

Class	Number	Percent
Irons	42	6.6
Stoney-Irons	12	1.9
Chondrites	523	82.8
Achondrites	56	8.7

Additional definition of micrometeorite composition has been obtained with the "Venus Fly Trap" (ref. 4). A survey of 17.8 mm^2 of the "Fly Trap" sampling area indicated 133 particles varying in size from 0.1 to 1 micron. Eleven particles greater than 1 micron in diameter were found by extending the surveyed sampling area to 18.5 mm^2. Although electron microscopy diffraction patterns of some particles indicate compositions of nickel monoxide and taenite, reference 4 classifies the particles in the three broad terms: fluffy, medium, and high density.

Whipple, in reference 6, stated that the majority (greater than 90 percent) of meteors were of cometary origin and defined the comet composition as an icy conglomerate that binds mineral particles together. The low density, high porosity, and frangibility of meteoroids is also indicated by flaring meteors (those having varying luminosity). As discussed in reference 7, a dynamic pressure of 1/50 of an atmosphere will cause a meteoroid to shatter. The conglomerate structure and related low bulk density will have a minimum particle size. For smaller sizes the bulk density will increase to the density of mixtures of the heavier elements (in some comets, nickel and iron) that have been identified by spectral emissions of comets.

The most recent publication of Whipple, reference 8, uses a single meteoroid density throughout the mass range. The density of 0.44 gm/cm^3 was obtained by simultaneous solution of luminosity and drag equations for several meteors.

Meteoroid Velocity

The geocentric velocity of the primary particle flux (not including the vicinity of the moon having secondary ejecta) can vary from 11 km/sec to 72 km/sec. The lower limit corresponds to the gravitational potential of the earth; the upper limit is the summation of the earth's orbiting velocity plus the parabolic velocity at 1 A.U., in our solar system, of a retrograde particle in the ecliptic plane. The radar measurement of the velocity of 11,073 meteors by McKinley of the National Research Council of Canada (ref. 9) as shown in figure 1 indicates very few meteors have hyperbolic trajectories and hence geocentric velocities > 72 km/sec and these could have been changed by planetary attraction. It is to be noted the data of figure 1 is for a VM $\approx$ 6 and less. The average velocity for a constant mass cannot be obtained from this figure because the meteor intensity (ion density) increases with velocity and results in an increased detection of smaller meteors and does not detect the increased number of these small meteors having a lower velocity. The velocity variation with visual magnitude as presented in reference 10 assumes a geocentric velocity of 28 km/sec for meteors in the range of visual magnitude of 0 to +7. The increasing influence of radiation pressure with decreasing particle size is taken into consideration by reducing the velocity 1 km/sec per visual magnitude to a constant value of 15 km/sec at a visual magnitude of 20; 15 km/sec is assumed constant for all larger visual magnitudes. In reference 8, Whipple uses a mean velocity of 22 km/sec.

MODEL METEOROID ENVIRONMENT

Average Primary Sporadic Meteoroid Flux

The meteoroid environment for near-earth, cislunar and lunar operations is a slightly modified form of the environment submitted in reference 8 to take into consideration new data and to simplify the application to vehicle design. The unshielded meteoroid flux will be a modification of the flux-mass relation, presented for an average velocity of 30 km/sec by Whipple as follows:

$$\log N = -1.34 \log m + 2.68 \log (0.44/\rho) - 14.48$$

N = number of particles/sq meter-sec

m = mass in grams

This equation has been modified to exclude earth shielding, increase the density to 0.5 gm/cm^3 (the trend of the actual density

variation was previously discussed) and gives particles/ft^2-day:

$$\log N = -1.34 \log m - 10.423$$

The increase in density will give a slight conservatism in the predicted number of particles for a given mass. It has been postulated in reference 11, but is not generally accepted nor proven in the measurements of reference 12, that for particles less than 10^{-8} gm the particle concentration decreases with distance from the earth's surface at a rate inversely proportional to the distance to the 1.4 power, to a minimum value at 10^5 km. This decrease has not been applied to the meteoroid environment. The flux-mass relation is illustrated in figure 2. The minimum particle size cutoff corresponds to a 0.5 gm/cm^3 density with a particle diameter of 4.1 microns and a 7 gm/cm^3 density with a particle diameter of 0.16 micron. The aforementioned flux-mass relation will define the primary sporadic meteoroid flux for near-earth, cislunar and lunar operations. The use of this equation states a mass of 1 gm for a visual magnitude of zero, and a visual magnitude-mass relation as follows:

$$m_n = m_o \, 10^{-0.4 \, VM_n}$$

where

VM = Visual magnitude

m_n = Mass at VM of n

m_o = Mass at VM of o

The prescribed flux is a yearly average and does not include the month-to-month variation illustrated in figure 3 that has been measured for visual magnitudes equal to and less than 5.

Meteor Showers

Noticeable increases in the average hourly rate of meteor activity occur at regular intervals during the calendar year. This increase is due to the earth's passage through a stream of particles traveling in similar heliocentric orbits and generally assumed to be cometary debris. The orbital elements, periods of occurrence, and ratio of maximum accumulative meteor stream flux to the sporadic meteor flux of 18 of the more prominent showers as determined from references 13, 14, and 15 are listed in table I.

Figure 4 illustrates the orbital paths of some of these showers relative to the ecliptic plane, at 1 A.U.

The contribution of each stream to the accumulative meteor stream flux for a calendar year is schematically illustrated in figure 5. For simplification the flux is considered constant for the entire period of stream activity. This sketch illustrates the inability to have a preferential orientation, because of simultaneous occurrence of more than one stream.

The rate of meteor influx varies with time for each stream; however, the variation is not well defined. For this model environment, the rate of meteor influx versus time for a stream is represented by a triangle or trapezoid (with the maximum rate of meteors per hour corresponding to the maximum value of the triangle or trapezoid). A triangle represents a stream having a maximum period of activity of one day or less; a stream with maximum activity longer than one day is represented by a trapezoid. The base of the triangle (the sporadic meteoroid background) corresponds to the total time of stream activity. A straight line variation from sporadic to maximum stream flux is assumed for the beginning and ending of each shower.

The F variation for each of the 18 major streams is illustrated in figure 6 and the integrated stream meteor flux for a calendar year is presented in figure 7.

It should be noted that figures 6 and 7 apply only for a visual magnitude of +4 and brighter (that is a mass of 2.5×10^{-2} and larger) and extrapolation of this integrated magnification factor to the smaller particle sizes (fainter visual magnitudes) is not valid.

Measurements of flux and the variation of flux with magnitude have been made in the visual magnitude range 0 to +3 and the radar magnitude range +5 to +7 for a number of streams. There is a direct correlation between visual and radar magnitude, hence the radar measurements are applicable to the visual magnitude scale. The data obtained in the ranges quoted indicate that the flux-visual magnitude slope is approaching zero at the fainter visual magnitudes. If the curve of flux versus visual magnitude is continuous and does not change sign, then the flux at the fainter magnitudes will be less. The fluxes of 3 streams are presented in figure 8. The slopes of the flux versus visual magnitude of Perseids and Geminids decreases (approaches zero) with decreasing mass; however, the slope of the Arietids increases for radar magnitudes greater than 2. Measurements of other streams also indicate a trend of decreasing slope of flux versus visual magnitude. Only one stream, the Geminids, has been measured at a radar magnitude of 8 (corresponding to a mass of 6.31×10^{-4} gms) to determine the variation of flux with time. The

results, presented in figure 9, show a marked decrease of F with decreasing mass. Therefore it seems realistic that the variation of F versus time that results in the integral curves of figure 6 should be reduced. The criteria adopted for the reduction of the F versus time curves for each stream is illustrated in figure 10. The maximum flux is considered unity for each stream and the duration of the stream is assumed to be the same as that of figure 6. It should be emphasized that these reductions are an interim measure dictated by the current lack of detailed knowledge of streams. The resultant integral of F versus time curves is depicted in figure 11. For meteoroids with masses $\geq 10^{-2}$ gms the F factors are defined in figures 6 and 7; for masses $< 10^{-2}$ gms the F factors are defined in figures 10 and 11.

Periodic Streams

Quadrantids, Giacobinids, Leonids, and Bielids are exceptions to figure 7. The Quandrantids have a predicted period of 13 years for the nucleus; however, measurements indicate an almost random (with respect to years) occurrence of high meteor flux rates of a nucleus. The 13 measured peak rates from 1864 to 1953 vary from 34 to 180 meteors/hour. The environment will use an arithmetic average of the measured maximums, that is, 80 meteors per hour, for masses $< 10^{-2}$ gms.

The Giacobinids have a well-defined nucleus with a period of 6.5 years, with negligible activity for intervening years. The 6.5-year period will cause a meteoroid influx every 6 or 7 years. On the 13-year period (1933) very heavy meteoroid influxes have been measured (1933 and 1946); however, the peak meteor flux increases over the sporadic background to 15 percent of the maximum meteor rate in $1\frac{3}{4}$ hours. In the next $1\frac{1}{2}$ hours the flux increases to maximum and reduces to 15 percent of maximum. The stream reduces to the sporadic background in another $1\frac{1}{4}$ hours; total stream lifetime of $4\frac{1}{2}$ hours. The $6\frac{1}{2}$ year period maximum F as shown in figure 7 is 20. The 13 year peak has been estimated to be 4,000 to 6,000 meteors/hour that might next occur in 1972.

The Leonid shower has a period of 33.25 years, the intervening years having very low flux rates of approximately 10 meteors per hour. The periodic influx of this stream can only be inferred from past and old observations. In 1831 to 1833 there was considerable shower activity culminating in an estimated rate of 10,000/hour in 1833. In 1866, a maximum of 5,000/hour was noted, decreasing to 1,000/hour in 1867 and 1868. In 1901 and 1903 there were 200 to 250/hour. In 1930 to 1932 the activity increased from 30 to 240/hour. The decrease in activity of this stream may be due to pertubations of the stream by the planets or the

lack of synchronization of the $33\frac{1}{4}$ year period with the earth's orbit. The 1965 to 1968 period would be 100 years from the last estimated rate of 5,000 to 1,000 meteors/hour and would put the earth-moon system into close proximity of the nucleus if the orbit has not been disturbed. The meteoroid environment has used, in figure 7, an F value of 25 based on the last two measurements having a 33-year period. Some relief to the shower intensity is obtained by the short time duration of the stream. The rate of meteors per hour increases from 10 percent of maximum to the maximum in 5 hours and decreases to 50 percent of maximum in another $1\frac{1}{2}$ hours.

The Bielids have indicated an almost constant yearly rate of 20 to 30 meteors/hour. The periodicity of the Bielids is 6.6 years. This would result in many observations of meteor showers associated with the stream nucleus. The constancy of the meteor rates from year to year indicates the stream has been perturbed and may be regarded as a constant stream.

As a result of the paucity of information on flux-mass relationships for the individual showers, the shower flux-mass relation is assumed to be the same as the law established for the sporadic activity. Thus, with the use of the ratios from figures 6 and 10, the flux-mass relation may be obtained for any desired period of shower activity, that is,

$$\log N_{showers} = -1.34 \log m - 2.68 \log V_s - 6.465 + \log F$$

where:

V_s = geocentric velocity of the meteor stream (km/sec)

F = ratio of accumulative meteor stream flux to the sporadic meteor flux

N = number of particles/ft^2-day

This equation takes into consideration the variation of mass with velocity as predicted by Opik in reference 16. The mass density of individual shower meteoroids will be the same as for the sporadics, assumed to be of cometary origin, 0.5 gm/cm^3.

The total number of impacts or penetrations for a spacecraft exposed to the meteoroid environment is the sum of the sporadic and shower contributions. For the sporadics, the omnidirectional flux dictates the use of total exposed surface area. In the case of the showers, the projected area is used and the period of shower activity may be obtained from table I or the abscissa of figure 6.

Secondary Flux

The lunar surface meteoroid flux will have a primary composed of the sporadic near-earth meteoroid flux, with or without the stream meteoroid flux, plus a secondary flux composed of ejecta as a result of primary impingement; the flux of secondary particles has been theoretically predicted in reference 17 to be $10^{3.83}$ of the primary and to persist to a lunar altitude of 30 km. The density of the ejecta is 3.5 gm/cm^3 with a maximum velocity of 2.4 km/sec. Assuming 55 percent of the primary particle kinetic energy is distributed in the ejecta particles (ref. 18) the average ejecta velocity is 200 meters/sec. The secondary flux presented in figure 2 includes a shielding factor of $\frac{1}{2}$, but does not take into consideration the percentage of the ejecta flux that have negligible velocities, nor the effect of showers.

The ejecta flux-mass relation for a sporadic primary can be expressed as:

$$\log N_{ejecta} = -1.34 \log m - 6.59$$

and for a shower primary as:

$$\log N_{ejecta} = -1.34 \log m - 2.68 \log V_s - 2.635 + \log F$$

In the general case (ejecta from sporadic and shower):

$$N_{ejecta} = 10^{3.83} \times N_{sporadic} + 10^{3.83} \times N_{shower}$$

Shield Factor

The position of a spacecraft in relation to a shielding body will reduce the incident flux. The shielding factor ζ is defined as follows:

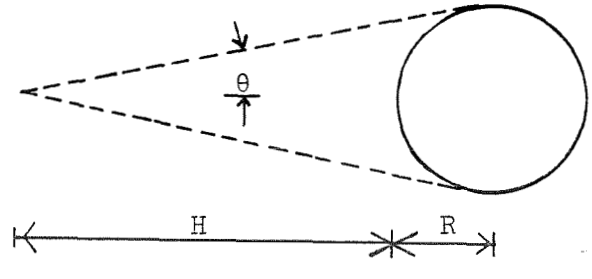
$$\zeta = (1 + \cos \theta)/2$$

and

$$\sin \theta = R/(R + H)$$

R = Radius of shielding body

H = Altitude from shielding body



PROJECTED MODIFICATIONS OF THE MODEL METEOROID ENVIRONMENT

The continued research in meteoroid technology will cause modifications to the model meteoroid environment as presented in this paper. Based upon known uncertainties and the areas under investigation, the following revisions are to be expected.

Sporadic Meteoroids

1. The slope of flux versus mass of meteoroids will not be constant throughout the mass range.
2. The density will vary for various mass ranges, at least for the smaller masses.
3. The average velocity will be replaced by a velocity dependent upon particle mass.

Stream Meteoroids

1. Flux versus mass and time during intercept with the earth's orbit will be made for the major streams.
2. The flux variation in portions of the orbits will be defined.
3. Density of particles in streams may be predicted.

Secondary Flux

1. Will be defined in terms of kinetic energy versus particle size.
2. The velocity distribution of the ejected mass.

CONCLUDING REMARKS

The near-earth and cislunar meteoroid environment is composed of a primary meteoroid flux of sporadic and stream meteoroids. The flux-mass relation for the sporadic population is as follows:

$$\log N = - 1.34 \log m - 10.423 \ (\text{particles/ft}^2\text{-day})$$

The meteoroid density is 0.5 gm/cm^3 for all particle sizes. The velocity of the sporadic meteors is assumed constant for all particle sizes at 30 km/sec.

Flux-mass relationships applicable to periods of shower activity during the course of a calendar year are defined as:

$$\log N_{shower} = -1.34 \log m - 2.68 \log V_s - 6.465 + \log F \text{ (particles/ft}^2\text{-day)}$$

where F is the ratio of the shower to sporadic hourly rates given in figure 7 and V_s is the geocentric velocity of an individual shower as given in table I. The mass density for all shower meteoroids is 0.5 gm/cm^3. The effects of showers on spacecraft may be based on the projected area.

The lunar environment (within 30 km of the lunar surface) is composed of the primary sporadic and shower meteoroid flux plus a secondary flux. The secondary flux is defined as follows:

1. Sporadic

$$\log N_{ejecta} = -1.34 \log m - 6.59$$

2. Showers

$$\log N_{ejecta} = -1.34 \log m - 2.68 \log V_s - 2.635 + \log F$$

The ejecta density is 3.5 gm/cm^3 and the average velocity considered to be 200 meters/sec.

A planetary shielding factor is to be used in conjunction with the sporadic population in the vicinity of the earth and the moon. The shielding factor ζ is defined as follows:

$$\zeta = (1 + \cos \theta)/2$$

where

$$\sin \theta = R (R + H)$$

R = radius of shielding body

H = altitude above shielding body

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TABLE I.- ORBITAL ELEMENTS FOR MAJOR METEOR STREAMS

Name	Period of Activity	Date Max.	F_{max}	Ω (deg)	π (deg)	ω (deg)	i (deg)	ϵ	q (a.u.)	a (a.u.)	Velocity Geocentric (km/sec)	Velocity Heliocentric (km/sec)	Period Years
Quadrantids*	Jan 2-4	Jan 3	8.0	282	92	166	67	0.46	0.97	1.7	42	39	13
Lyrid	April 19-22	April 21	.85	30.5	--	210	81	0.88	0.90	---	48	40	19.8
η - Aquarid	May 1-8	May 4-6	2.2	45	152	108	162	0.96	0.66	17.95	64	41	11
O - Cetid	May 14-23	May 14-23	2.0	238	89	211	34	0.91	0.11	1.3	37	33	1.5
Arietid	May 29-June 19	June 6	4.5	77	106	29	21	0.94	0.09	1.6	38	34	1.8
ζ - Perseid	June 1-16	June 6	3.0	78	--	59	4±2	0.79	0.35	1.6	29	35	2.2
β - Taurids	June 24-July 5	June 28	2.0	276	162±4	246±4	9±4	0.86	0.36	2.5	31	37	3.3
δ - Aquarid	July 26-Aug 5	July 28	1.5	305	101±2	156±2	24±5	0.96	0.08	1.8	40	35	3.6
Perseid	July 15-Aug 18	Aug 10-14	5.0	142	--	155	114	0.96	0.97	23	60	42	109.5
Giacobinid*	Oct 9-10	Oct 10	20	196	--	172	30.8	0.72	0.99	3.5	23	41	6.57
Orionid	Oct 15-25	Oct 20-23	1.2	29.3	103	87.8	163	0.92	0.54	6.32	66	41.5	--
Arietid, Southern	Oct-Nov	Nov 5	1.1	27	150	122	6	0.85	0.30	1.91	28	36	2.64
Taurids, Northern	Oct 26-Nov 22	Nov 10	0.4	221	160	308	2.5	0.86	0.31	2.16	29	37	3.2
Taurids, Night	Nov		1.0	220	160	300	3	0.86	0.3	2.1	37	37	3.3
Taurids, Southern	Oct 26-Nov 22	Nov 5	0.9	45	157	112	5.1	0.85	0.36	2.39	28	38	3.69
Leonid*	Nov 15-20	Nov 16-17	0.9	234	49	179	162	0.92	0.99	12.8	72	41	33.25
Bielids*	Nov 15-Dec 6		2.5	250	109	223	13	0.76	0.88	3.6	16	39.5	6.6
Geminid	Nov 25-Dec 17	Dec 12-13	4.0	261	--	324	24	0.90	0.14	1.4	35	35	1.7
Ursids	Dec 20-24	Dec 22	2.5	270	--	210	5±3	1.0	0.92	--	37	42	--

*Periodic streams

F = ratio of maximum accumulative meteor stream flux to the sporadic meteor flux for mass size $\geq 10^{-2}$ grams

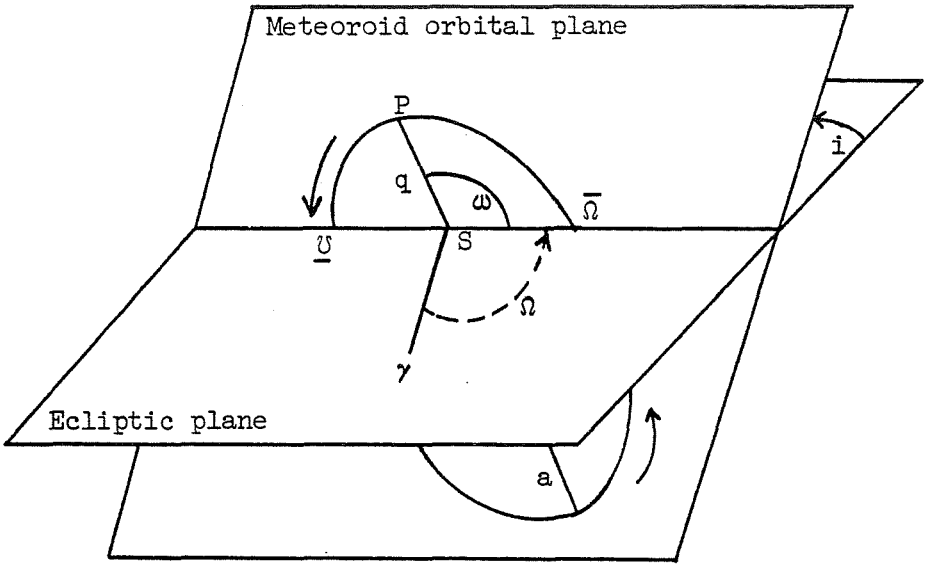


TABLE I.- ORBITAL ELEMENTS FOR MAJOR METEOR STREAMS - Concluded

a = semi-major axis (astronomical units)

p = point of perihelion

q = perihelion distance (astronomical units)

S = sun

γ = heliocentric position of the vernal equinox

ϵ = eccentricity

i = inclination of meteoroid orbital plane

$\pi = \Omega + \omega$

Ω = longitude of ascending node

$\overline{\Omega}$ = ascending node

$\underline{\upsilon}$ = descending node

ω = latitude of perihelion

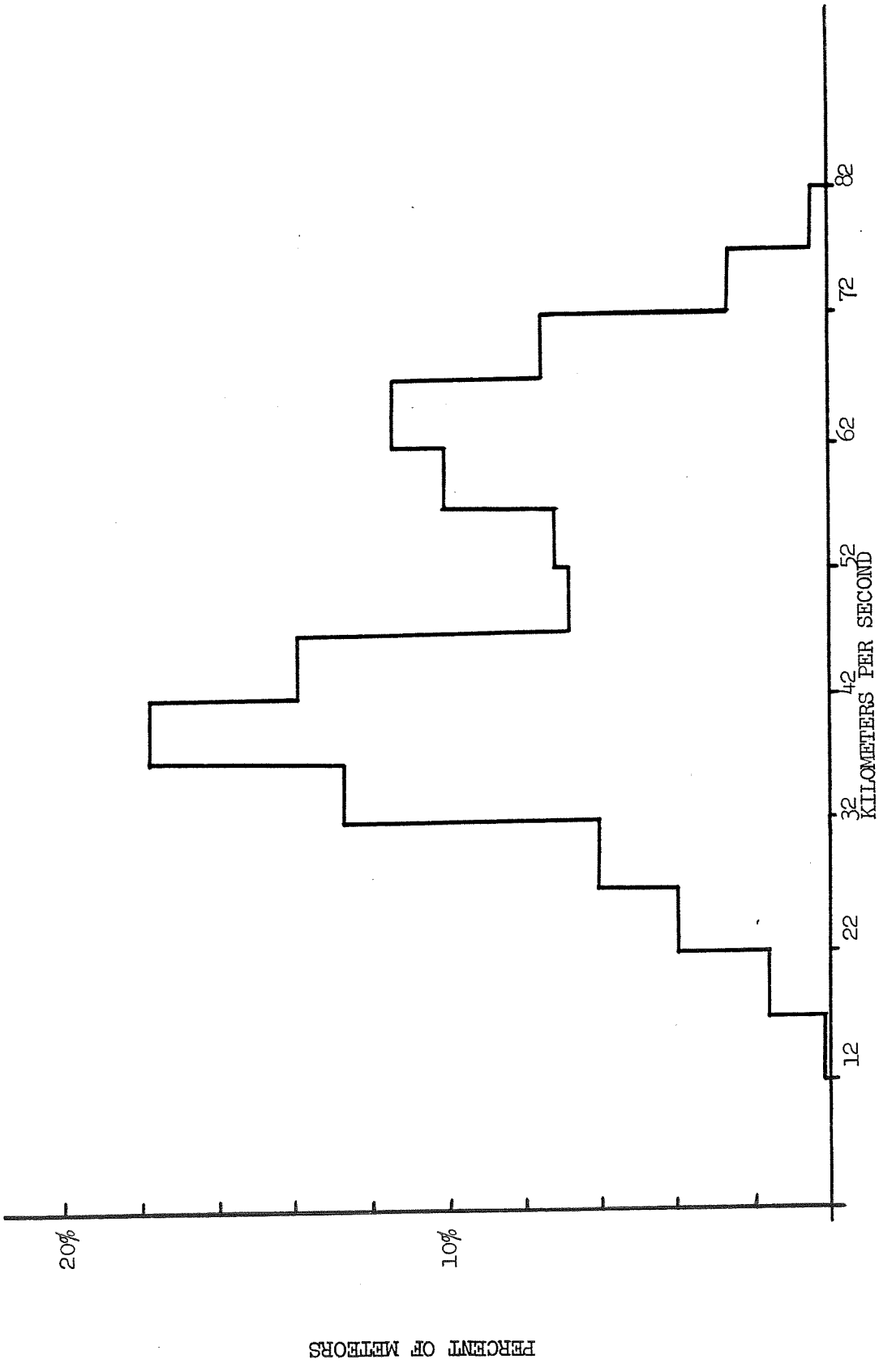


Figure 1.- Velocity distribution of 11,073 meteors

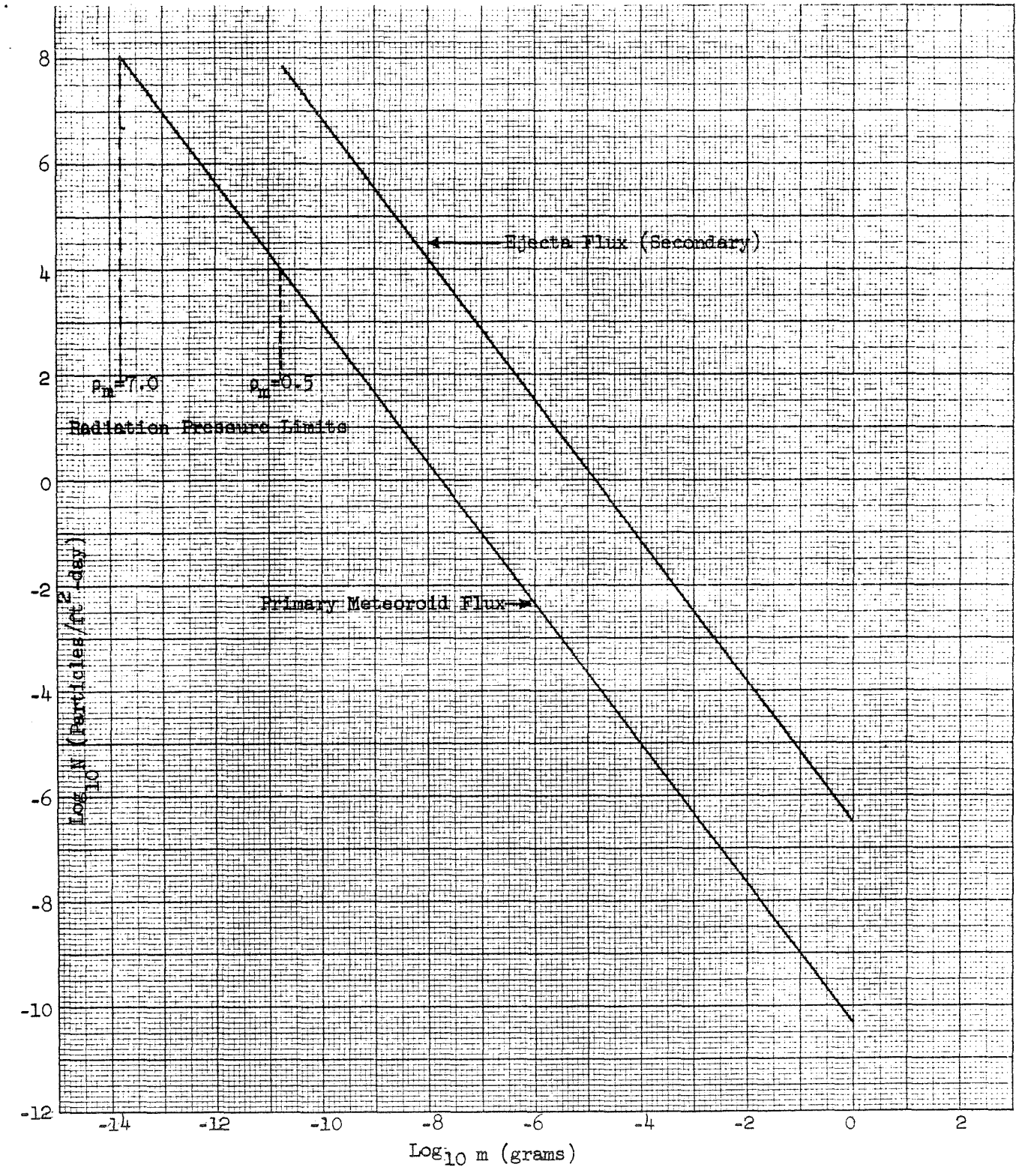


Figure 2.- Earth, cislunar, and near lunar meteoroid environment

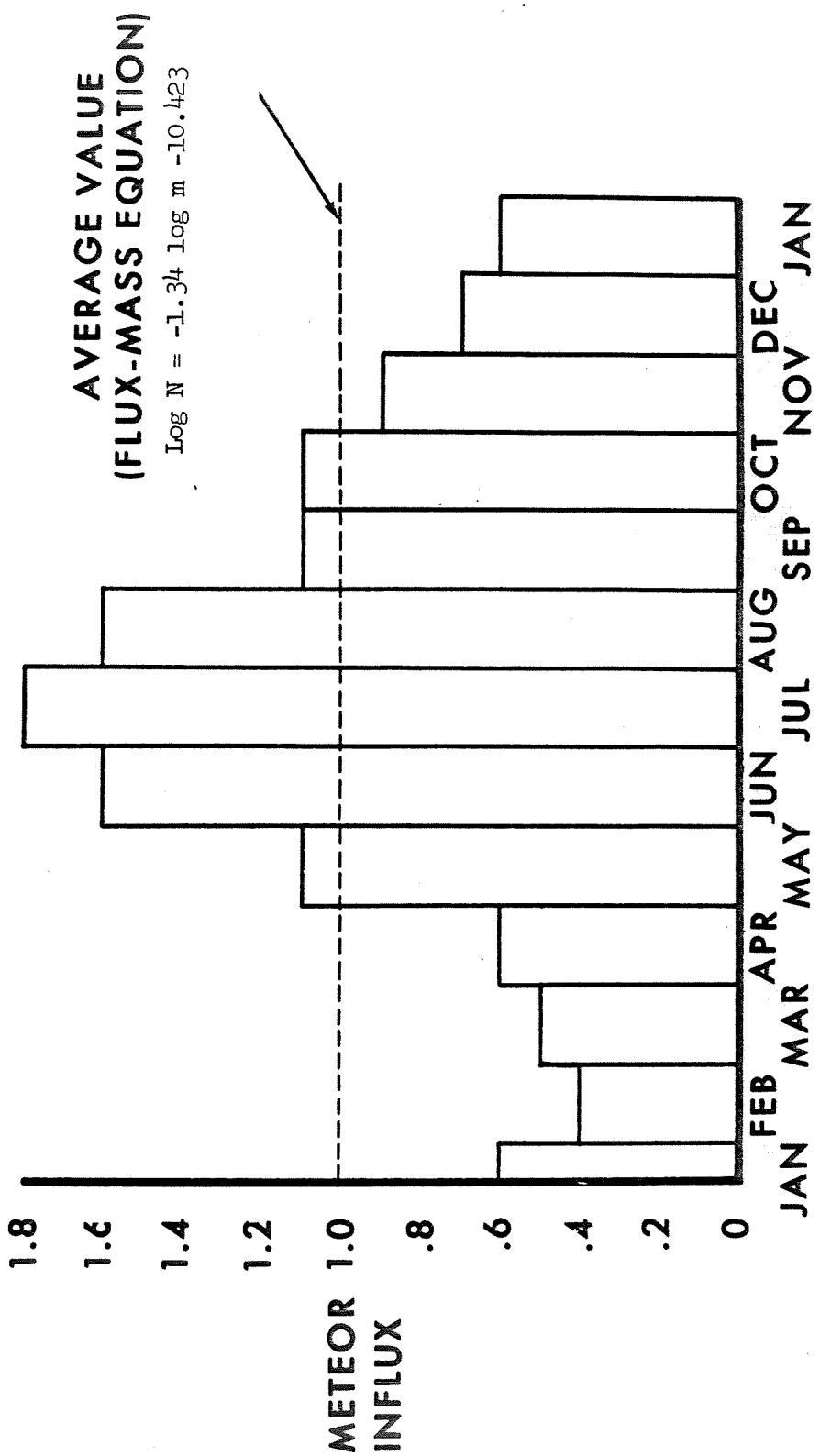


Figure 3.- Yearly sporadic meteor influx

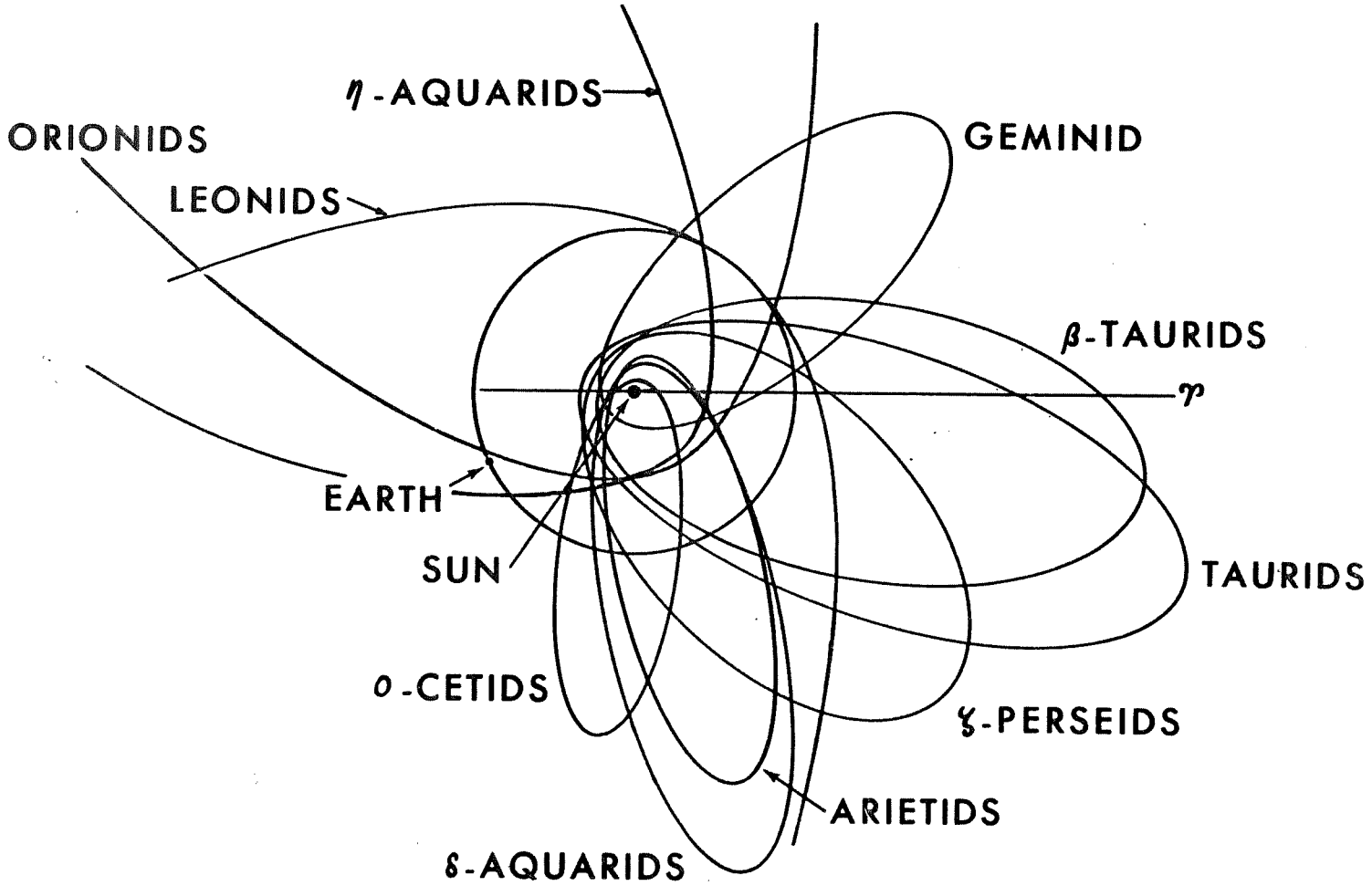


Figure 4.- Orbits of meteor streams intersecting the ecliptic plane

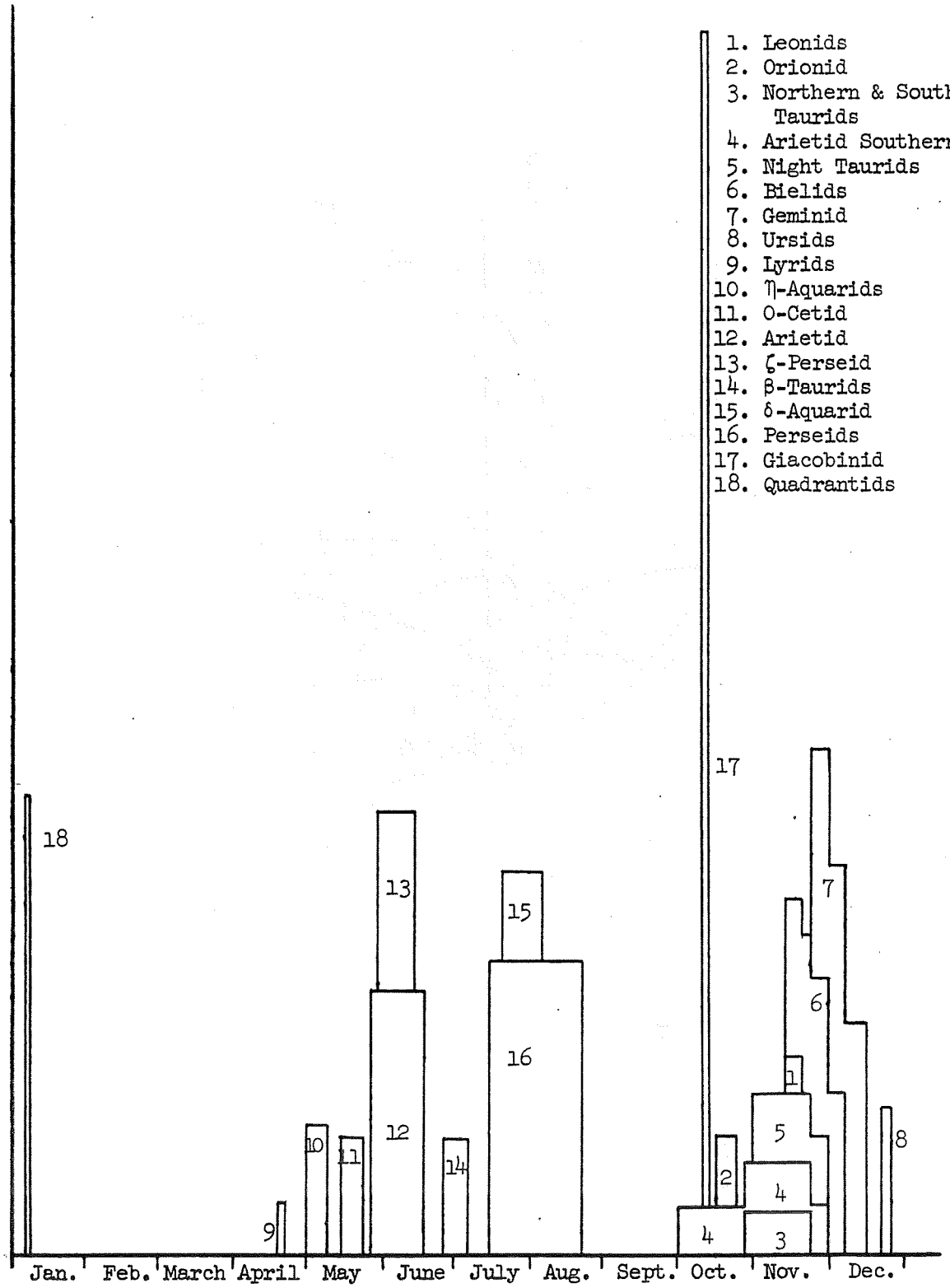


Figure 5.- Accumulative meteor stream flux for a calendar year

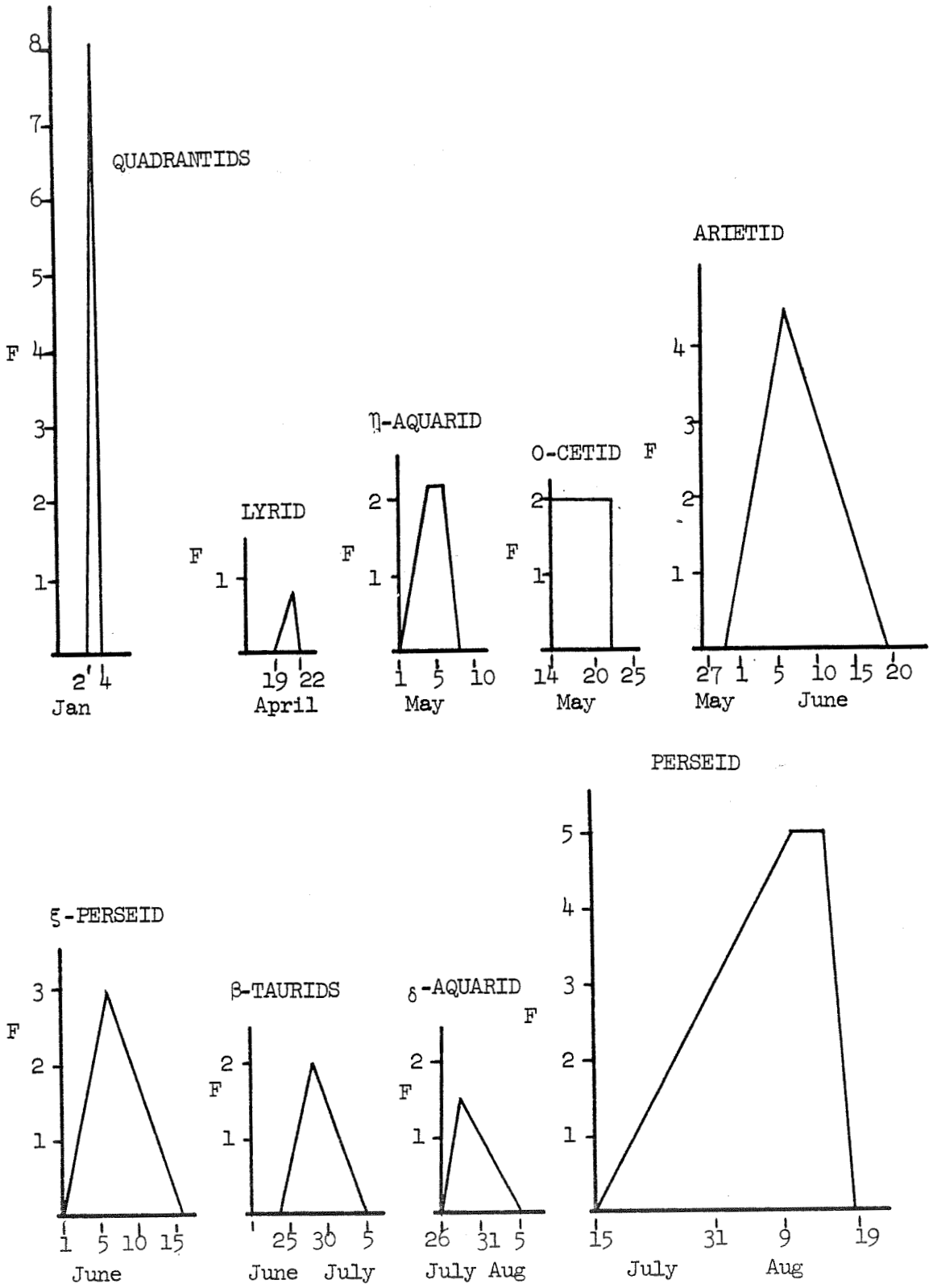


Figure 6.- F ratio versus date of activity of major meteoroid streams of mass size $\geq 10^{-2}$ grams

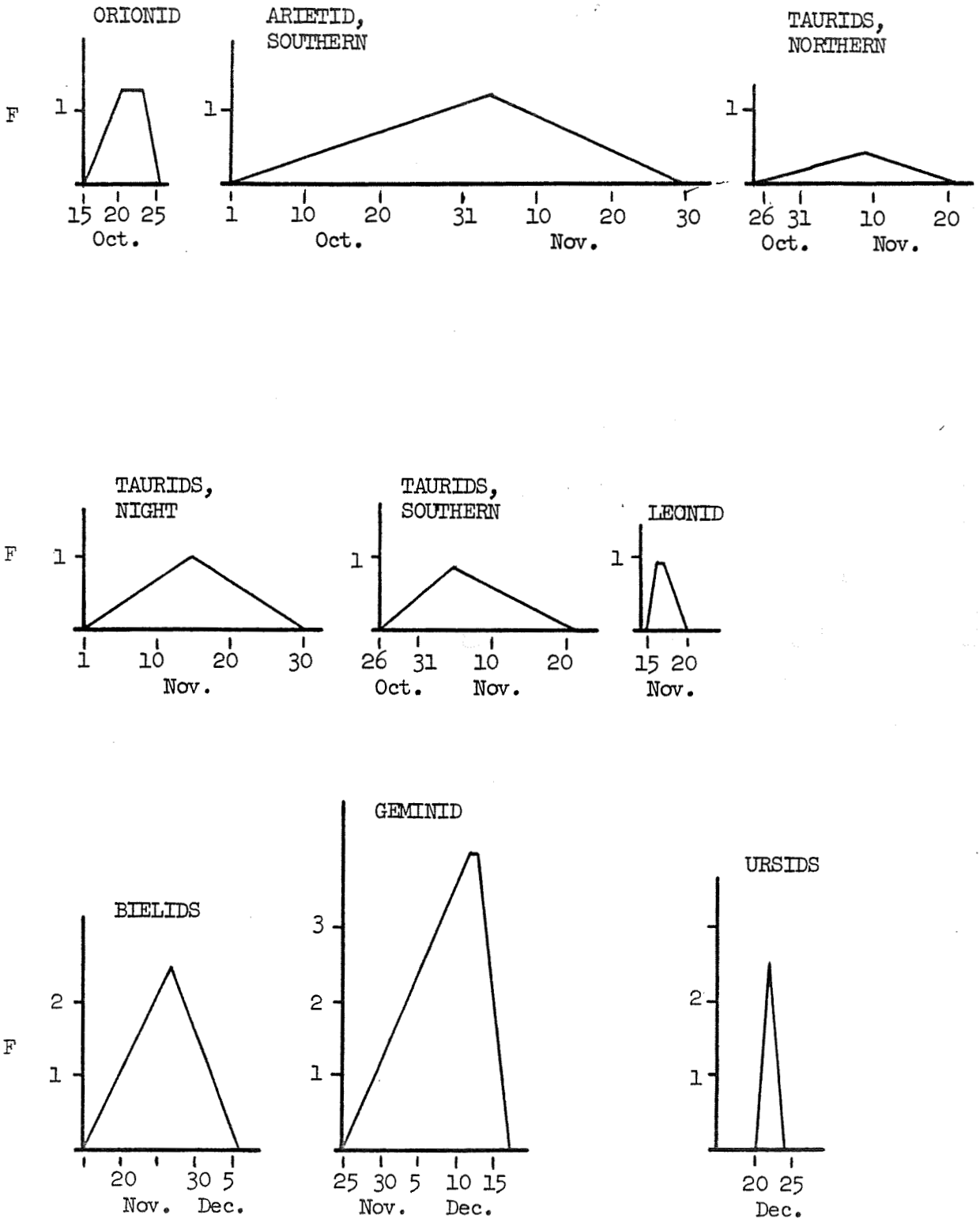


Figure 6.- F ratio versus date of activity of major meteoroid streams of mass size $\geq 10^{-2}$ grams - Concluded.

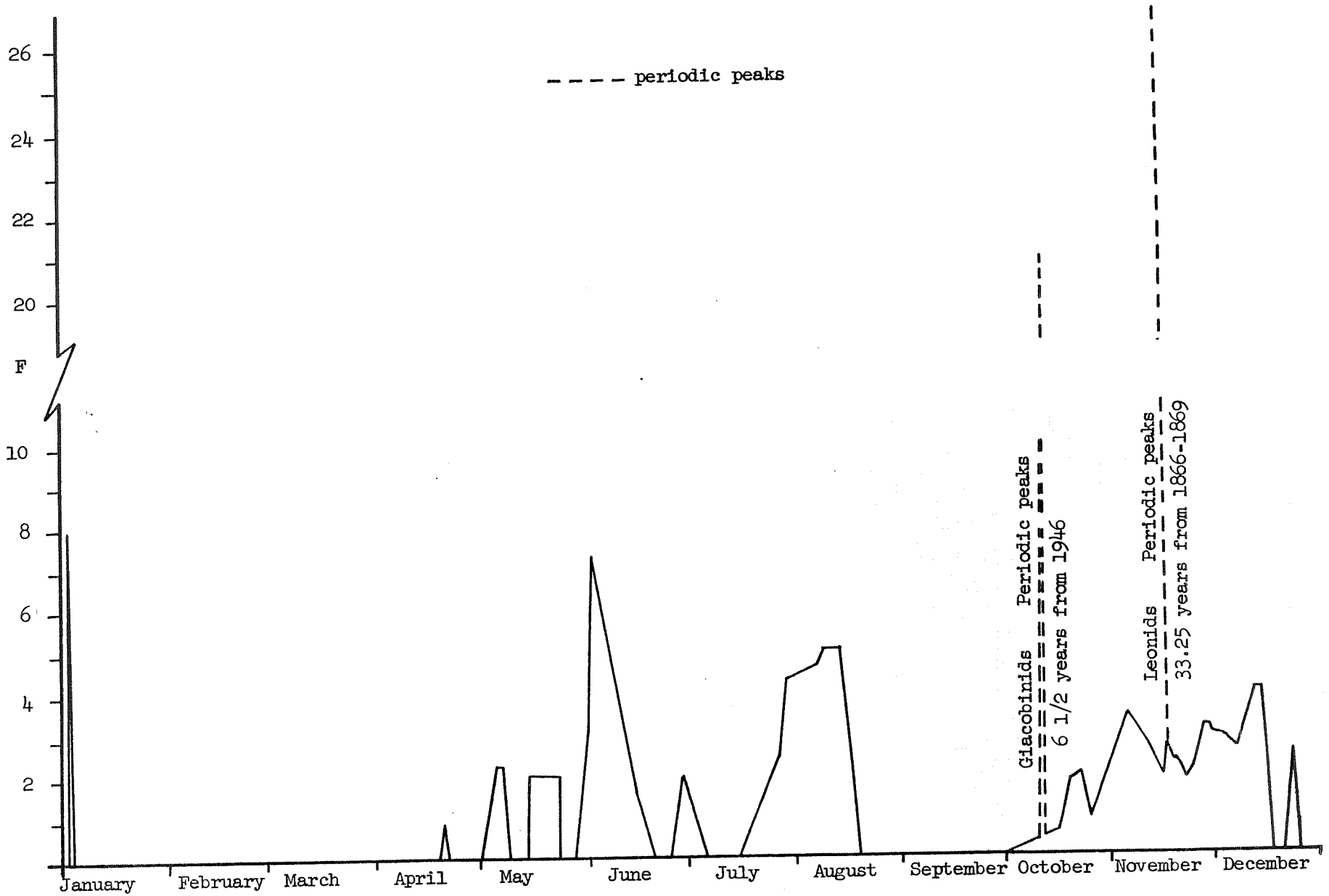


Figure 7.- Ratio of accumulative meteoroid stream flux to the sporadic meteoroid flux for $m \geq 10^{-2}$ grams.

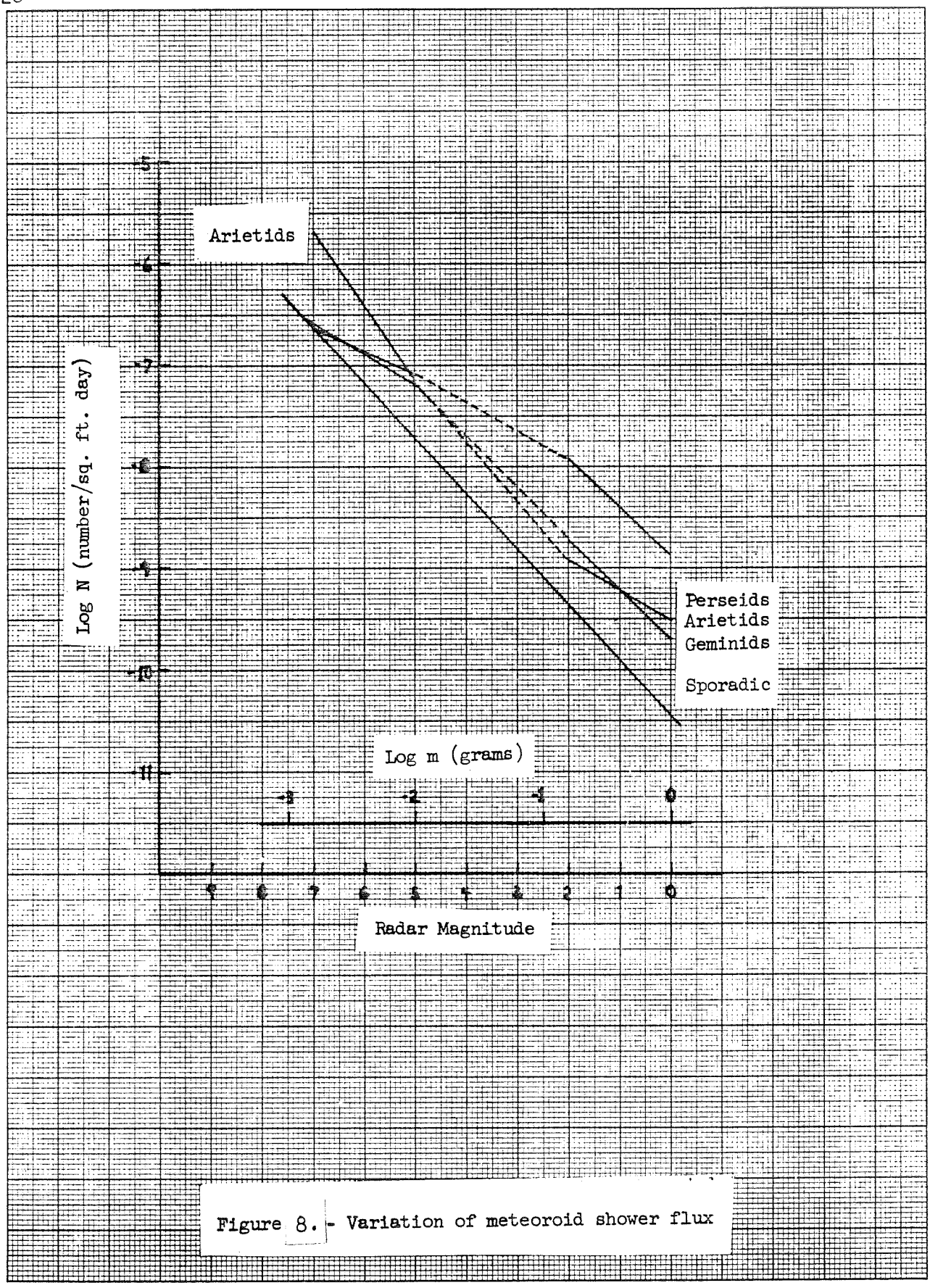


Figure 8. - Variation of meteoroid shower flux

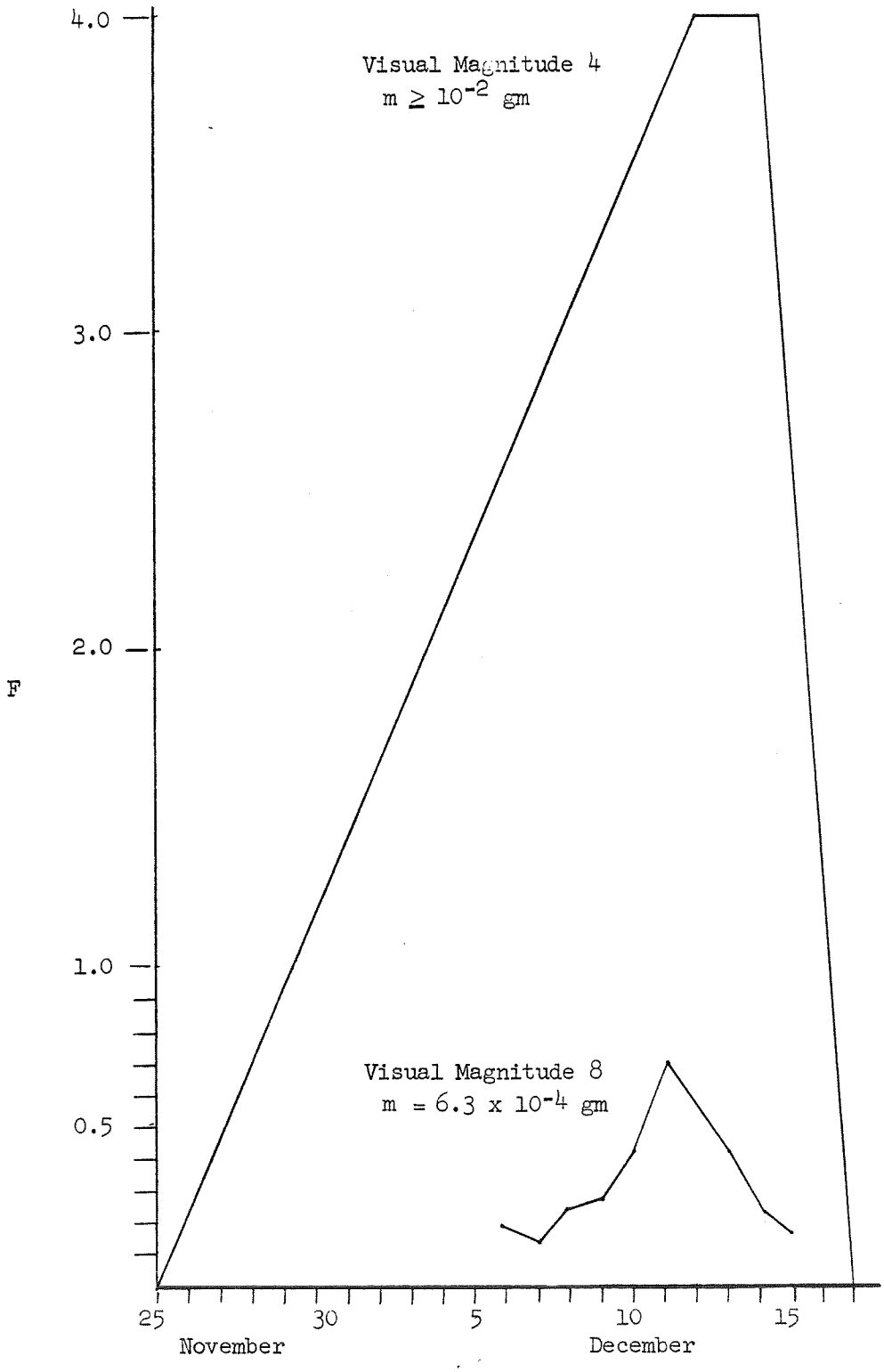
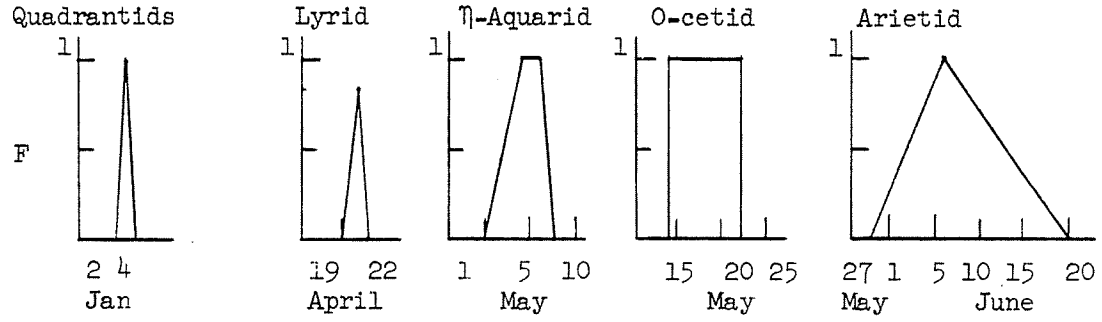


Figure 9.- Comparison of F ratio at visual magnitude 4 and 8 for Geminid stream



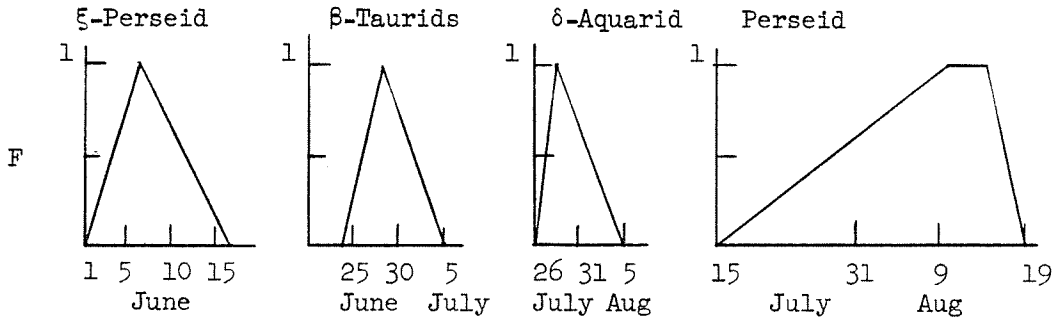


Figure 10.- Revised F versus date of activity of major roid meteoroid streams for mass size $< 10^{-2}$ grams

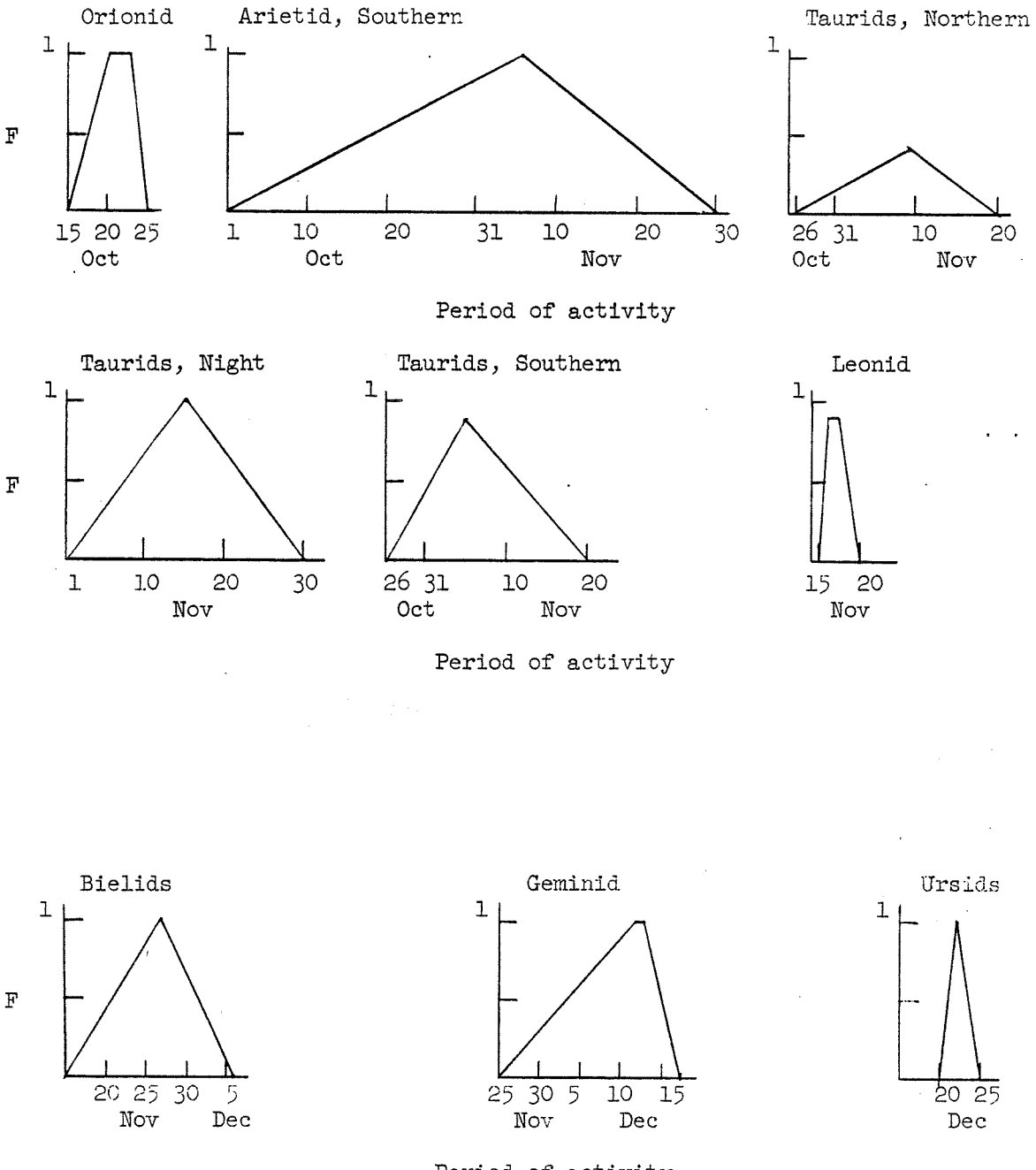


Figure 10.- Revised F versus date of activity of major meteoroid streams for mass size $< 10^{-2}$ grams - Concluded.

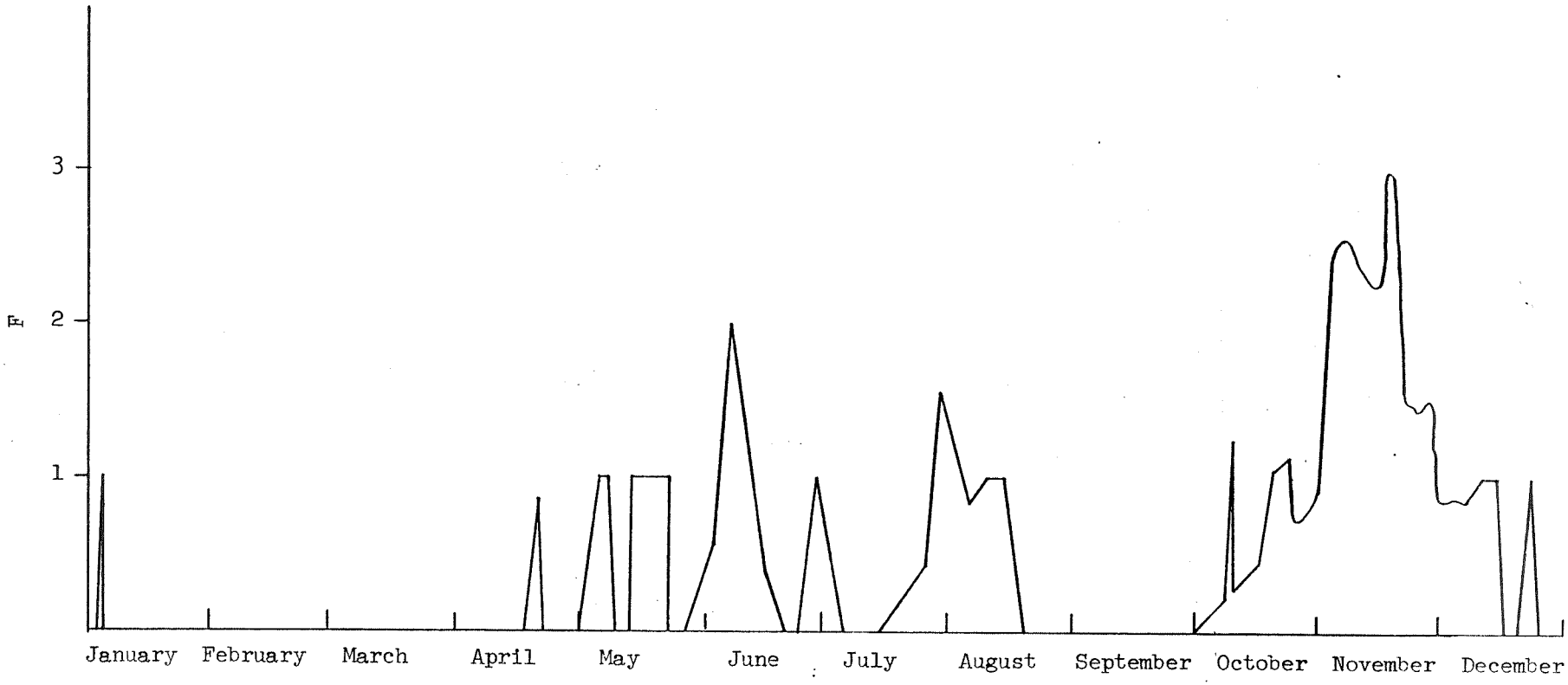


Figure 11.- Ratio of accumulative meteoroid stream flux to the sporadic meteoroid flux for $m < 10^{-2}$ grams in a calendar year.